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Influence of HMPA on Reducing Power and Reactivity of $SmBr_2$

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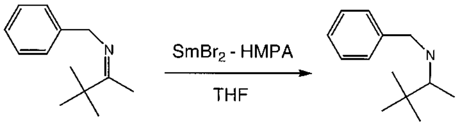
ABSTRACT



Addition of HMPA to $SmBr_2$ in THF produces a reactant with an estimated redox potential of -2.63 ± 0.01 V (vs $Ag/AgNO_3$). This powerful reductant is capable of reducing ketimines and alkyl chlorides at room temperature. Although the structure of the reductant has not been established, it is nonetheless a powerful addition to the arsenal of samarium-based reductants currently utilized.

Reagents based on samarium are widely employed in organic synthesis.[1,2] Samarium diiodide (SmI_2) is the most widely used Sm(II) reductant because it is soluble in electron-donor organic solvents such as THF at moderate concentrations. It is also stable for long periods of time if stored in an inert atmosphere. The general utility of SmI_2 lies in the fact that it can initiate tandem bond-forming reactions through radical or anionic processes.[3] Many traditional organic reactions such as the Grignard or Reformatsky reactions can utilize SmI_2 in place of magnesium or zinc with improved yields. Although SmI_2 is a versatile reductant, it does have a number of limitations. Many reactions of SmI_2 require the addition of HMPA (or other additives) to be promoted. While SmI_2 or SmI_2-additive combinations easily reduce alkyl and aryl iodides, bromides are reduced at a slower rate and alkyl chlorides require photochemical conditions[4] or high temperatures.[5]

Other Sm(II) reductants have been used for organic transformations, including samarium(II) triflate, dicyclopentadienylsamarium, and samarium dibromide ($SmBr_2$). Samarium(II) triflate was found to promote higher diastereoselectivity than SmI_2 in the addition of alkyl iodides to ketones.[6] Dicyclopentadienylsamarium produces stable organosamarium intermediates in reactions with allylic and benzyllic halides.[7] Kagan and co-workers have shown that $SmBr_2$ is an excellent reagent for pinacol coupling and is superior to both SmI_2 and $SmCl_2$.[8] Recent work in our laboratory has shown that the combination of LiBr and SmI_2 produces soluble $SmBr_2$ and that this reagent is a more powerful reductant than SmI_2.[9] In our present study, we examine the influence of HMPA on $SmBr_2$ and investigate the reactivity of the resulting complex.

Redox potentials are one of the most important parameters that need to be measured for Sm(II) reducing agents because they provide valuable insight into the reducing power of the Sm(II) reductant. Recent studies with samarium diiodide have shown that the redox potential can be changed by addition of a coordinating cosolvent such as hexamethylphosphoramide (HMPA) or other donor solvents and ligands.[10] Recent

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studies in this lab have shown that change of the coordinating halide from iodide to bromide also changes the reducing power of samarium complexes. The large number of coordinating solvents and ligands makes it increasingly important to obtain redox values for each, so that future synthetic work can be performed in a more logical manner. This will further increase the ability to fine-tune a reducing agent for a particular reaction.

To examine $SmBr_2$ complexes, cyclic voltammograms of the reductant with increasing amounts of HMPA were measured in THF. Figure 1 shows voltammograms obtained for $SmBr_2$ and $SmBr_2$ containing 50 equiv of HMPA. It is immediately apparent that the reducing ability of $SmBr_2$ is greatly enhanced by addition of large amounts of HMPA from the shift in the oxidation peak (520 mV) as well as the shift in the reduction peak (510 mV) to more negative values. Addition of more than 50 equiv of HMPA showed no further change in the redox potential. Redox potentials were estimated from the oxidation and reduction peaks of the quasi-reversible voltammograms and found to be -2.07 ± 0.03 V for $SmBr_2$ and -2.63 ± 0.01 V for $SmBr_2$−HMPA (vs $Ag/AgNO_3$ reference).

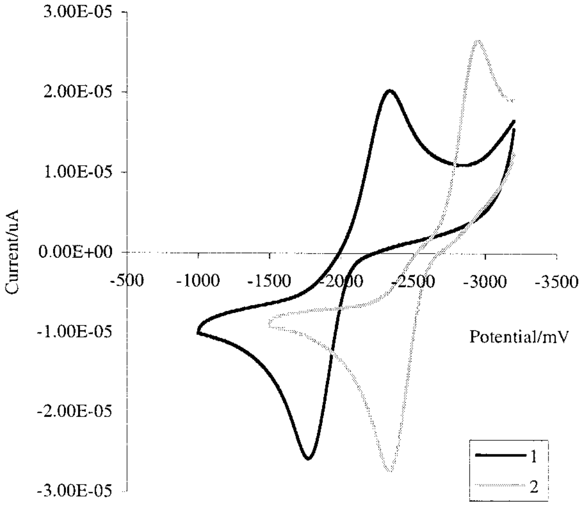

Figure 1. Cyclic voltammograms of (1) $SmBr_2$ and (2) $SmBr_2$−HMPA.

It is interesting to compare the CVs of $SmBr_2$−HMPA and SmI_2−HMPA (Figure 2) and note the similarities and differences between the two complexes. Both species interact with HMPA in a manner that increases their reducing ability. However, SmI_2 is known to show a change in reducing power that shows an intermediate with a maximum at 4 equiv[11] and then another at greater than 10 equiv of HMPA,[12] whereas $SmBr_2$ requires 50 equiv of HMPA to maximize its reducing power. The SmI_2 species at 4 equiv of HMPA was initially identified by us as $[SmI_2(HMPA)_4]$. Recent work of Daasbjerg and co-workers has provided evidence that the solution structure is $[Sm(THF)_2(HMPA)_4]I_2$, and a careful VPO analysis in our lab concurs with this finding.[12] Furthermore, recent work of Daasbjerg provides strong evidence that SmI_2 containing greater than 10 equiv of HMPA produces the octahedral complex $[Sm(HMPA)_6]I_2$.[12] In their CV experiments, increasing the amount of HMPA from 4 to 10 equiv shows a shift toward increasing irreversibility of the Sm complex. The $SmBr_2$ complex does not exhibit this irreversibility with increasing amounts of HMPA. Comparison of the voltammograms of $SmBr_2$ with 50 equiv of HMPA and SmI_2 containing 50 equiv of HMPA shows significant differences in both redox potential and reversibility, indicating that the $SmBr_2$−HMPA complex is not $[Sm(HMPA)_6]^{2+}$ (Figure 2).

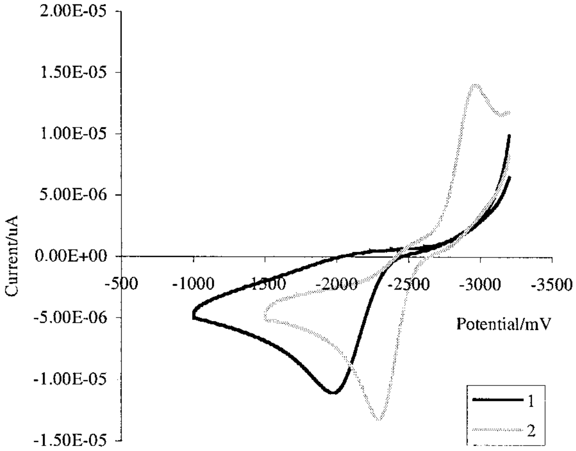

Figure 2. Cyclic voltammograms of (1) SmI_2−HMPA and (2) $SmBr_2$−HMPA.

Solutions of $SmBr_2$ and $SmBr_2$−HMPA were further analyzed using UV−vis spectroscopy. Figure 3 shows the spectra obtained for SmI_2, SmI_2−HMPA (50 equiv), $SmBr_2$,

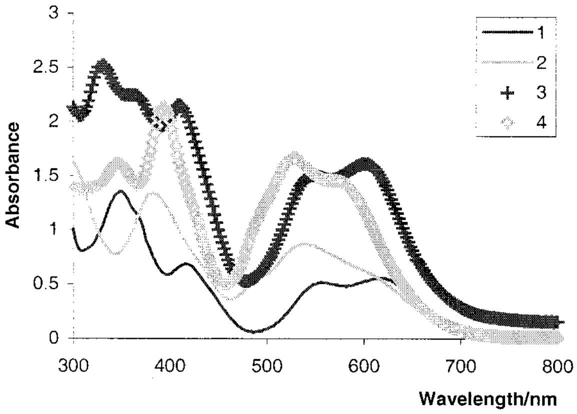

Figure 3. UV−vis spectra of (1) SmI_2, (2) SmI_2−HMPA, (3) $SmBr_2$, and (4) $SmBr_2$−HMPA.

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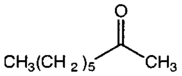
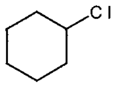
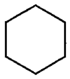
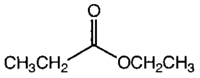
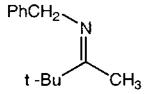
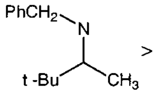
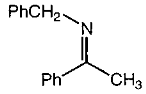
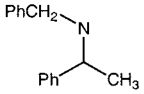
and $SmBr_2$−HMPA (50 equiv) in THF solvent. There are three primary absorbance regions for $SmBr_2$, at 410, 548, and 604 nm. For $SmBr_2$−HMPA, these peaks have been shifted to the shorter wavelengths 394, 526, and 582 nm. The bands between 500 and 650 nm for Sm(II) complexes have been ascribed to f−d transitions, although this assignment is not a certainty.[13] The two shortest wavelengths are consistent in terms of relative intensities. However, the peak at 604 nm for $SmBr_2$ loses a significant amount of its relative intensity upon the addition of HMPA. These shifts to shorter wavelengths show that the Sm(II) complex is absorbing a higher amount of energy. A reasonable conclusion is that HMPA, being a more tightly bound ligand than THF, is increasing the ligand field strength of the system. In transition metals, increased ligand field strength increases the splitting of the d-orbitals responsible for absorption.[14] A similar conclusion could be drawn here, that f-orbital splitting is occurring to a larger extent, increasing the amount of energy necessary for an excited state to be achieved. While 4f orbitals are highly shielded in lanthanide elements, it has been reported that perturbations of up to 0.1 eV (9.6 kJ mol^{-1}) can occur from ligand effects.[15] The maximum shift of 22 nm by the $SmBr_2$ absorptions upon the addition of HMPA is equivalent to 4 kJ mol^{-1}, well within this established literature value. Our studies show there is clearly a relationship between the addition of HMPA to $SmBr_2$ and the change in the energies of the ground and excited-state orbitals, whatever the transitions may be.

It is interesting to compare the UV−vis spectra of SmI_2 and $SmBr_2$ and their HMPA complexes. Both SmI_2 and $SmBr_2$ absorptions shift to shorter wavelengths upon addition of HMPA. While SmI_2 and $SmBr_2$ complexes show absorptions at 618 nm (SmI_2) and 604 nm ($SmBr_2$), these peaks broaden significantly upon the addition of HMPA. Although the exact species in solution for the bromide complexes cannot be discerned from these data, careful examination of the UV−vis spectra in Figure 3 shows that both $SmBr_2$ and $SmBr_2$−HMPA are different than their SmI_2 analogues. This supports electrochemical evidence presented earlier in this paper and clearly shows that addition of excess HMPA to $SmBr_2$ does not produce the octahedral complex $[Sm(HMPA)_6]^{2+}$.

To examine the synthetic utility of $SmBr_2$ and $SmBr_2$−HMPA, several reactions with functionalities that are typically difficult to reduce were performed. Table 1 lists some substrates that were exposed to $SmBr_2$−HMPA, the obtained products, and their respective yields. The pinacol coupling of 2-octanone provides a 70% yield of product with the balance of the reaction mixture being 2-octanol. More interesting is the reduction of alkyl chlorides. Both 1-chlorododecane and chlorocyclohexane are reduced quantitatively to the corresponding alkanes in less than 2 h at room temperature. Although chloroalkanes can be reduced by SmI_2−HMPA, the reaction requires elevated temperatures and extended periods of time. Thus, $SmBr_2$−HMPA is the reductant of choice for alkyl chloride reductions. We also found that $SmBr_2$−HMPA is not useful in ester reduction. All attempts to reductively couple alkyl chlorides with esters resulted in reduction of the chloroalkane and recovery of the ester.

Table 1. $SmBr_2$−HMPA-Mediated Reactions

substrate	conditions	product	yield[a]
	rt, 24 hrs	pinacol coupling[b]	69%
$CH_3(CH_2)_8CH_2Cl$	rt, 2 hrs	$CH_3(CH_2)_8CH_3$	> 99%
	rt, 2 hrs		> 99%
	rt, 24 hrs	No reaction	
	rt, 15 min		> 99% (90%)[c]
	rt, 15 min		> 99%

[a] Yields based on GC−MS analysis. [b] 2-Octanol found in 20% yield. [c] Isolated yields in parentheses. [d] General conditions: 0.25−1.0 mmol substrate, 2−2.5 equiv $SmBr_2$−HMPA (50 equiv HMPA), under nitrogen atmosphere (See Supporting Information).

Another reaction that we explored was the reduction of ketimines. Although the reductive dimerization of aldimines has been carried out with SmI_2,[16] there are few examples of the reduction of ketimines.[17] Treatment of the *N*-benzyl imines of acetophenone and pinacolone with $SmBr_2$−HMPA produced the corresponding amines in less than 15 min at room temperature. The reduction product from the *N*-benzyl imine of pinacolone was isolated in a 90% yield. We are currently exploring the reduction of less hindered ketimines with $SmBr_2$−HMPA to examine the possibility of carrying out reductive coupling reactions that lead to vicinal diamines.

In conclusion, we have studied the influence of HMPA on $SmBr_2$. While coordination of HMPA to $SmBr_2$ produces a more powerful reductant in a manner analogous to SmI_2, the reductant is distinct from those formed between SmI_2 and HMPA. The combination of $SmBr_2$ and HMPA provides a powerful reducing reagent capable of reducing carbon−chlorine bonds and imines. We are currently carrying out a

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careful spectroscopic and thermochemical study of Sm(II) reductants in order to learn more about the relationship between the structure and activity of these important reducing reagents. The results of these experiments will be reported in due course.

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Supporting Information Available: Experimental procedures, UV−vis spectra, and cyclic voltammograms. This material is available free of charge via the Internet at http://pubs.acs.org.

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